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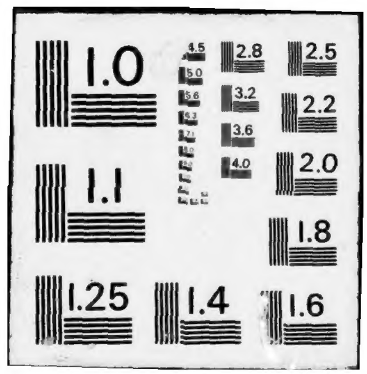
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U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A034 260

DESTATOR TEST PROGRAM EVALUATION

BATTELLE COLUMBUS LABORATORIES, OHIO

8 JULY 1976

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REPORT NO. CG-D-[redacted]-76

DESTATOR TEST

PROGRAM EVALUATION

FINAL REPORT

JULY, 1976

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PREPARED FOR

U.S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
OFFICE OF RESEARCH AND DEVELOPMENT
WASHINGTON, D.C. 20590

Rept. no. changed per Ensign Judson, Coast Guard. M Crumbacker 12 Jan 77 DDC-TCA

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Technical Report Documentation Page

1. Report No. 130 CG-D-[redacted]-76	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Destator Test Program Evaluation		5. Report Date: July 8, 1976
		6. Performing Organization Code
7. Author(s): S. A. Hawk and R. B. Reif		8. Performing Organization Report No.
9. Performing Organization Name and Address: Battelle-Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201		10. Work Unit No. (TRAIS): 733842.1
		11. Contract or Grant No.: DOT-CG-23223-A
12. Sponsoring Agency Name and Address: Department of Transportation, United States Coast Guard, 400 Seventh Street, S. W., Washington, D. C. 20590		13. Type of Report and Period Covered: Final Report, February 26, 1974 – August 31, 1976
		14. Sponsoring Agency Code: G-DSA-1

15. Supplementary Notes

The U. S. Coast Guard Office of Research and Development's Technical Representative for the work performed herein was LCDR MICHAEL W. TAYLOR

16. Abstract

Explosions that occurred in three very large crude tankers in December, 1969, called attention to a probable electrostatic problem related to washing operations in the large tanks. In response to that conclusion, the Cierva Electrooptical Corporation of Madrid, Spain, developed the Destator, a system designed to sense charge in a tank being cleaned and to control the magnitude of that charge. The United States associate of Cierva Electrooptical (CincoTech Corp.) obtained a contract with MARAD for testing this system aboard the S.S. Universe Japan. This report is an evaluation of those tests. Conclusions and comments are given.

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17. Key Words: Tanker explosions, tanker cleaning, tanker safety, electrostatics, static electricity, Destator, S.S. Universe Japan	18. Distribution Statement: Document is Available to the Public through the National Technical Information Service; Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This is a final report that summarizes work conducted under Task Order No. 13, Contract No. DOT-CG-23223-A, from February 26, 1974, to August 31, 1976. The work was performed by the Columbus Laboratories of Battelle under the auspices of the U. S. Coast Guard, with Lt. Michael Taylor serving as program monitor. The principal investigators were Mr. Samuel A. Hawk and Mr. R. B. Reif.

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FINAL REPORT

on

DESTATOR TEST PROGRAM EVALUATION

to

U. S. COAST GUARD

from

BATTELLE
Columbus Laboratories

July 8, 1976

1.0 INTRODUCTION

Explosions that occurred in three very large crude tankers in December, 1969, called attention to a probable electrostatic problem related to washing operations in the large tanks.[1, 2, 3, 4, 5] Much of the effort subsequently applied in the study of this problem has been directed by the fact that these explosions occurred in large tankers. However, explosions also have occurred on small crude carriers during washing operations.

As is well known, for any explosion to occur, the volume must contain an explosive mixture and a source of ignition. Presently, vessels transporting combustionable materials endeavor to either remain outside the limits of combustion -- either by exclusion of oxygen by means of inerting with flue gas or nitrogen -- or by maintaining a mixture within cargo tanks either too rich or too lean to explode in the presence of a potential ignition source. In any inerting system, however, the possibility exists that the system may fail or not be operative for some period of time.

In recognition of this potential failure and the likelihood that at least some of the tanker explosions have been electrostatic in nature, the Cierva Electrooptical Corporation of Madrid developed the

Destator system.* The Destator Model CDC727 consists of a sensing head, an electronics package, and a water-spraying unit. The sensor, located at the end of the Destator, is a low-impedance, rotating-vane, field meter. This unit, with its auxiliary electronics, senses the magnitude of the electrical field at the sensor and indicates the polarity of the charge around the sensor. Directly above the sensor in the Destator package is a Water Ionizing Gun (WIG) unit. This unit contains twelve small water sprayers each with an induction ring. When a potential of one polarity is applied to the induction ring, the droplets of the spray are ejected with the opposite polarity. The signal from the sensor is processed electronically and a potential of the same polarity as the charge in the tank is applied to the induction rings of the wigs. Thus, as the tank atmosphere becomes charged, the field meter (sensor) produces a signal which is converted to a potential on the induction ring of the water sprayers (wigs). The spray from the wigs (oppositely charged to that of the net charge in the tank volume as "seen" by the sensor) neutralizes the charge in the tank. If no charge exists in the tank, no electrostatically induced explosions can occur.

The electronics package would normally be located in the pump control room so that the tank condition could be continually known to the pump control room personnel.

To provide a test for the Destator under actual operating conditions, the CincoTech Corporation of Los Angeles, California (the U. S. associate of Cierva Electrooptical Corp.), obtained a contract with the Maritime Administration, U. S. Department of Commerce, calling for testing of the Destator aboard a VLCC vessel of the Universe class. Because of the potential impact that the results of the project between CincoTech and MARAD might have upon the operational safety of bulk petroleum carriers, MARAD established a Technical Evaluation Board. Membership in the board was comprised of representatives of governmental

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* A detailed description of this system is provided in References 7, 8, and 9.

and industrial organizations concerned with the operational safety of bulk petroleum carriers. The primary purpose of this Board was to review, critique, and evaluate all phases of the testing of the Destator. Major participants on the Board included:

(1) U. S. Department of Commerce, Maritime Administration, Office of Commercial Development and Office of Ship Construction

(2) CincoTech Corporation

(3) Gulf Oil Transportation Company

(4) Gulf Research and Development Corporation

(5) United States Coast Guard, Office of Research and Development

(6) American Bureau of Shipping

(7) Americal Hull Insurance Syndicate

In addition to these members, guests having various interests and expertise were invited to selected meetings from time to time. Battelle-Columbus participated as an observer and advisor for the U. S. Coast Guard.

2.0 SCOPE

This report is based on the visual observations and analysis of the test data acquired during the at-sea tests conducted aboard the S.S. Universe Japan. The purpose of this task was to evaluate the test plans submitted by CincoTech, inspect the installation of the Destator, observe the tests with the Destator, evaluate the final CincoTech report covering those tests, and provide to the U. S. Coast Guard an overall evaluation of the tests.

Although a copy of the final report from CincoTech to MARAD had not been received, the Coast Guard instructed Battelle to submit this final report without further delay.

3.0 TEST PROCEDURES AND CONDITIONS

As a result of detailed agreements between the Technical Evaluation Board and CincoTech, the installation and placement of the sensors as well as the type of tests to be conducted were specified. Two sets of tests were authorized. One set was carried out in gas-free tanks which had been thoroughly cleaned and recoated just prior to the tests; the other tests were carried out in nongas-free tanks aboard the same carrier after it had completed two round trips.

All tests were conducted in Tanks 8 center (8C) and 8 port (8P) which are located just forward from the pump and engine rooms.

3.1 Sensor Location

3.1.1 Gas-Free Tests

3.1.1.1 Tank 8C. Destator II was 2 meters aft and 2 meters to the starboard from the center of the tank and 6 meters below deck. The tube sensor was on a line with the starboard guncleans and 1/3 the distance from the forward guncleans to the aft guncleans. The wall sensor was mounted on the side of a vertical structural rib approximately 17 meters below deck midway between the side bulkheads. The Chevron sensor was lowered through a small opening in the deck about 3 meters forward of the aft gunclean on the port side.

3.1.1.2 Tank 8P. In the port tank, Destator I and the tube sensor were approximately midway between the longitudinal bulkheads and 3 meters below deck. The wall sensor was mounted on a horizontal platform approximately 7 meters from the inside bulkhead and 17 meters below deck. The Chevron sensor was lowered through a deck opening midway between the Destator and the aft gunclean.

After completion of the gas-free tests, the wall sensors were removed from both tanks inasmuch as the vanes would be submerged in crude. They were not installed for the nongas-free tests.

3.1.2 Nongas-Free Tests

3.1.2.1 Tank 8C. Destator II was mounted the same as for the earlier tests, approximately 2 meters aft and 2 meters to starboard from the center of the tank and 6 meters below deck. It had been stored in its housing in the tank for approximately 6 months since the first tests. Sensors 1 and 3 were installed in tubes extending some 5 meters below deck and forward from the Destator. Sensor 1 was on the port side of the tank approximately 1/3 the distance from the forward to the aft guncleans. This was the same location as the tube sensor in the earlier gas-free tests. Sensor 2 was positioned similarly on the starboard side of the tank.

3.1.2.2 Tank 8P. Destator I and two tube sensors, Sensors 1 and 3, were located on a line between the fore and aft guncleans. Sensor 3 was forward of the Destator and Sensor 1 was between the Destator and the aft gunclean.

3.2 Gas Concentration

During the gas-free tests, the gas concentration meter gave no reading at any time in either Tank 8C or 8P. Both tanks were inerted with flue gas during the nongas-free tests.

3.3 Numbering of Guncleans

In the port tank, the guncleans were numbered from bow to stern.

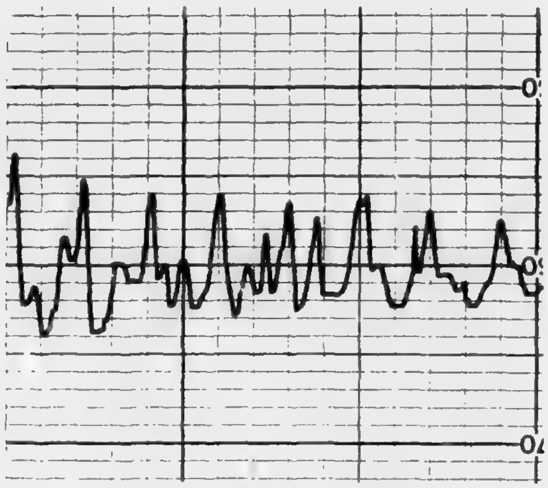
In the center tank, guns were numbered from port to starboard and from bow to stern. Gun No. 1 was forward on the port side; Gun No. 2 was forward on the starboard side, No. 3 was aft on port side, and No. 4 was aft on the starboard side.

4.0 TEST RESULTS

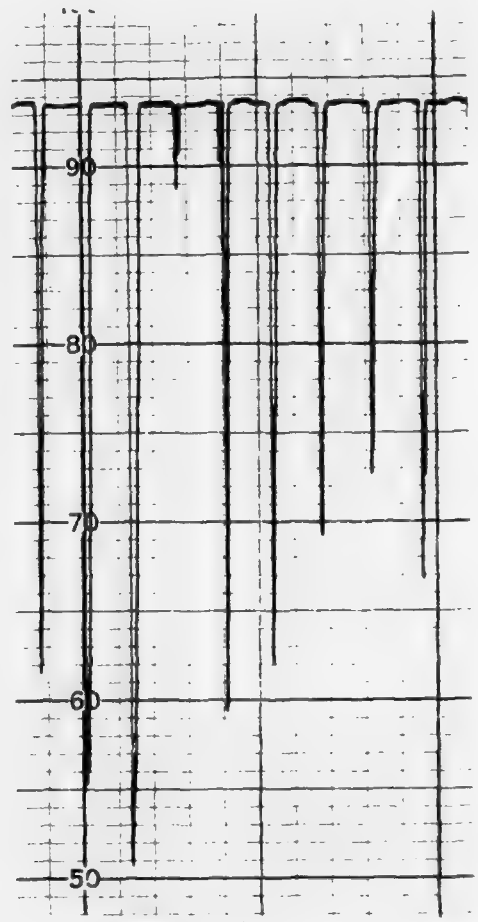
Throughout the tests, whenever the guncleans were in operation, the meter readings were pulsating. That is, the curve appeared to be the combination of two effects. One element of the curve was smooth; the other element of the curve was made up of sharp peaks and valleys. Several types of these characteristic curves (as recorded during the gas-free tests in Tank 8C) are illustrated in Figure 1. Curve (a) is the trace of the tube sensor (T) and illustrates the gradual rise in the recorded field with the random "negative" elements. Curve (b) is from the Destator sensor (D) and illustrates the saturated sensor at 15 kV/m with "negative" spikes. Curve (c) is the trace from the wall sensor (W). The spikes on Sensors T and D are attributed to the passage of water jets close to the sensor. The considerable trash on Sensor W is attributed to a direct hit into the head of the sensor. No meaningful values can be inferred from such a trace.

In the analysis and evaluation of these data, the actual value of the field was assumed to be the tops of the curves and, in general, the "spikes" were ignored. The justification for ignoring the spikes is that as soon as the guns were turned off, the curves smoothed out either at a value which would be interpolated from the preceding tops of the curves or slightly higher. In addition, many of the periods of spikes or trash as shown by the trace for Sensor W could be related audibly with the passing of a gunclean water jet.

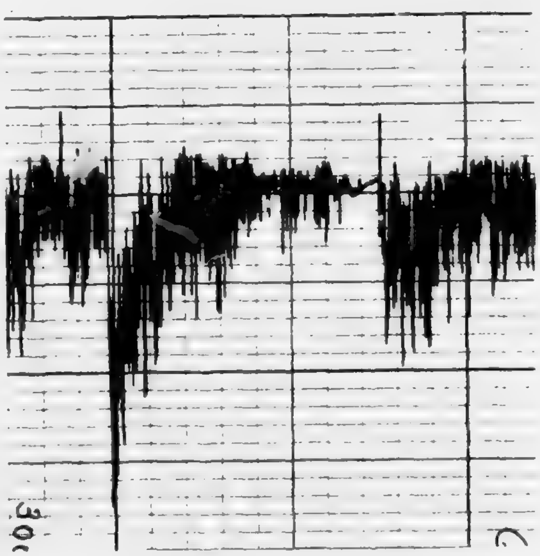
The readings for the Chevron sensor were read visually and recorded manually. This meter could be used only when elevation of the washing gun was at a low level because the sensor was suspended on the end of a line and the sensor would not withstand the shock of being hit with the spray. The readings from this sensor also varied but in a period which corresponded to the roll of the ship. Most of the readings were taken at a level of 6 meters below the deck, and when the ship rolled, the sensor swung several feet from a position normal to the deck. An excursion of this magnitude through the tank changes the position of



(a) Tube Sensor (T)



(b) Destator Sensor (D)



(c) Wall Sensor (W)

FIGURE 1. TRACES OF FIELDS RECORDED AT THE THREE CINCOTECH SENSORS

the sensor in the field as well as the volume which the sensor "sees". Therefore, the meter reading increased or decreased corresponding to the motion of the ship. An average value midway between the extremes is reported in this case so that the reading can be compared with those made when the motion of the probe was insignificant.

The values given for field throughout this report are stated as exact values. However, they are approximate because the meters were not calibrated in the tanks.* Also, the translation of points from the calibration curves to the recorder charts may introduce considerable error, particularly for small values of field.

4.1 Tests in Gas-Free Tank

Tests in the gas-free tanks were conducted during the period of May 28 through June 2, 1975, while the S.S. Universe Japan was en-route from Lisbon, Portugal, to Las Palmas, Canary Islands.

4.1.1 Tests in Tank 8C

4.1.1.1 Cleaning With Restricted Gun Rotation: Wigs Off. In the first tests, guncleans were pointed towards the corners of the tank and slowly rotated. The wigs were not in operation. After saturation of the sensors, the guncleans were turned off and the decay was monitored.

Before the guncleans were turned on, a positive tank charge was indicated by the sensor of Destator II (Sensor D) producing a field of 2-1/2 kV/m. The wall sensor (Sensor W) was zero with random negative spikes every few seconds, the tube sensor (Sensor T) was zero, and the Chevron sensor (Sensor C) was 5 kV/m. This was a steady-state condition--the result of residual charge from the previous day's operation. The guncleans were turned on in succession during the first 12 minutes of

* Reference Appendix A which discusses the importance of proper meter calibration.

the tests (1829 to 1841 hours) and were turned off after approximately 2-1/2 hours of operation. The field within the tank was then monitored for a period of 2 hours.

Destator. Immediately after the first gun was turned on, the field was affected at the Destator; after a short negative pulse, the field increased to 7-1/2 kV/m. At 1833, the second gunclean was turned on, the field momentarily dropped to less than 6 and then rose to 8 kV/m. At 1838, the third gun was turned on and sensor reading increased to saturation (over 15 kV/m). This value held constant throughout the test.

Wall. There was no reading at this sensor until 1833 when the second gun was turned on. The reading was very low. As succeeding guns were turned on, the field increased gradually, and after 30 minutes into the test, a constant field of about 12-1/2 kV/m with some peaks as high as 15 kV/m was recorded. When the guns were turned off between 2100 and 2108, the field reading was 16 kV/m. This field reading slowly decayed over the next 2 hours to a value of less than 5 kV/m at the end of the test at 2300.

Tube. Sensor T indicated no field until after the second gun was turned on. The reading then gradually increased to 15 kV/m after 30 minutes and 17 kV/m after 1 hour (1930). This value was constant until the guns were turned off. At that time, the reading increased to 19 kV/m and then began a slow decay to about 14 kV/m within an hour (2200) and a final value of 10 kV/m at the end of the test.

Chevron. The Sensor C reading increased sharply from an initial reading of 4-1/2 kV/m to 61 kV/m after all four guns were in operation. At 1850, the readings slowly oscillated from a low of about 50 kV/m (as low as 30 kV/m at one point) to a high of 110 kV/m. These variations appeared to correspond to the roll of the ship. For a comparison, a reading of about 90 was obtained at the same time that Sensor T indicated 17; Sensor D was saturated.

Most readings were at a 6-meter depth below the deck (approximately the level of the Destator).

After 30 minutes into the test (1900), the rolling of the ship decreased and the readings were fairly steady. At 1915, the reading was 100; this value held (within 10 percent) until the guns were stopped. The reading then rapidly rose to 140 kV/m and began a slow decay to 90 kV/m at 2145, 82 kV/m at 2200, 68 kV/m at 2230, and 60 kV/m at 2300.

Profiles of field strength at various depths in the tank produced smooth decay curves as expected with highest values of field measurements at 9 meters, the full length of the cable on the sensor.

4.1.1.2 Cleaning With Normal Gun Rotation: Wigs On. (May 31, 1975). This test was begun with neither the wigs nor the guncleans in operation and a residual field was observed at the Destator sensor. After a few minutes, the wigs were turned on. Gun No. 1 was turned on at 0750, No. 4 at 0847, and No. 2 at 1048. Considerable mechanical trouble was experienced with Gun No. 1. Its movement was on and off several times and its driving motor was finally replaced just after the second gun was in operation. The guns were turned off after 4-1/2 hours of operation, between 1150 and 1158, but the wigs remained on throughout the test.

Destator. Initially the Destator sensor indicated a residual field of 3-1/3 kV/m. This value immediately went to almost zero when the wigs were turned on. (A small ripple value of less than plus 1 kV/m was recorded.) The large test pulse of the Destator, 1 to 2-1/3 kV/m, was readily apparent.

After the No. 1 gun was started, the ripple doubled to a value of approximately 1-1/2 kV/m and the test pulse was about 4-1/2 kV/m. As each succeeding gun was started, the ripple increased incrementally. Between 0847 and 0948, the ripple was as high as 2 kV/m; between 0948 and 1048, generally the maximum was 3 kV/m but some peaks were up to 5 kV/m. After all guns were in operation, the peaks went as high as 9-1/2 kV/m.

As the guns were shut down, the sensor reading returned to zero. The ripple was 1 kV/m but decayed to less than 1 kV/m within 15 minutes.

Wall. The wall sensor did not show any response until 0915. At that time, the reading began to vary between zero and 2-1/2 kV/m. After all guns were operational, the sensor showed a peak as high as 5 kV/m. As the guns were turned off, the reading decreased to zero and remained steady.

Tube. This sensor remained at zero until the first gunclean was turned on. At that time, the reading jumped to 2-1/2 kV/m and after an immediate drop to 2 kV/m, gradually increased to 4 kV/m during the next half hour. At that time, Gun No. 1 stopped rotating and the field dropped to about 1-1/2 kV/m. The gun motor was restarted and the field returned to its former value within 20 minutes. After another drop to zero, the reading gradually increased to 4 kV/m by 0850, 7 kV/m at 0900, 9 kV/m at 0930, 11 kV/m at 1000, and 15 kV/m at 1143. After the guns were turned off, the decay was exponential to 7 kV/m within 15 minutes and to 0 after an hour.

Chevron. As in Test I, this sensor was consistently higher than the others but because of the wide fluctuations in the readings due to rolling of the ship, no further information of value is apparent. For example, with 3 guncleans in operation, the meter made its maximum excursion and was swinging between readings of 5 and 62 kV/m. In general, the readings were not over 40 kV/m.

4.1.1.3 Cleaning With Normal Gun Rotation: Wigs Off. (May 31, 1975). During this test, the guncleans were operated on their regular duty cycle of complete rotation. Wigs were on initially. Gunclean No. 1 was turned on at 1430, No. 4 at 1626, No. 2 at 1732, and No. 3 at 1735. Wigs were turned off at 1927 and guns off at 2117 to 2120.

Destator. Sensor D was turned on at 1422 and a 7 kV/m reading was indicated for about 1 minute until the wigs were turned on. Immediately the reading went to zero. After No. 1 gun was turned on, the

reading remained at near zero but with a 1 kV/m ripple sometimes negative and sometimes positive. The 5-minute test signal was readily apparent. When the gun was horizontal, a small increase in field was indicated but the field was still less than 1 kV/m. After two guns were operating, between 1645 and 1730, the record showed many spikes at the 3 to 4 kV/m level. The average was still much less than 2 kV/m. The higher frequency of spikes, as well as the increased magnitude, may have been due to the frequency of horizontal sweeps of the guns and the occurrence of both being horizontal at the same time. Between 1725 and 1745, the readings were again in the 1 kV/m region. During this period, Guns 2 and 3 were turned on. At 1745, a period of tall spikes was again recorded. Until 1825, many spikes in the range from 4 to 6 kV/m were recorded, but the average value was less than 2. A 5-minute period of relatively low values was again followed by a period with values similar to those shown just earlier.

After 5 hours of spraying, the wigs were turned off and immediately Sensor D saturated (over 15 kV/m) and remained so. When the guns were turned off after 7 hours of operation (2120), the sensor remained saturated until the wigs were turned on 45 minutes later. The reading immediately fell to less than 2 kV/m and continued to fall.

Two minutes after the wigs were turned on, they were turned off and the reading again immediately jumped to saturation. This indicates that the charge in the tank has not been eliminated but that the Destator wigs are blinding its sensor.

During the same period, the wall sensor continued to decay but the tube sensor also appeared to start an increase before it was shut off. The Chevron meter was pulled at 2209.

Wall. Sensor W indicated zero field until approximately 1445 at which time an abrupt signal (similar to that shown in Figure 1c) of 65 kV/m was given. This reading tapered off to zero within 15 minutes but was followed immediately by a second buildup to a peak of 60 and decayed to zero within 18 minutes. These bursts occurred throughout the

run and were attributed to direct hits by the guncleans. All values were negative polarity.

After the wigs were turned off, a gradual increase in field was recorded. Field measurements (positive) were as follows: 2-1/2 kV/m at 1930, 7 kV/m at 1945, 12-1/2 kV/m at 2000, and 20 kV/m at 2100. Superimposed on all these values were negative spikes. Typical plots are shown in Figure 2.

Charge continued to increase until the guncleans were turned off between 2117 and 2120. After the guns were stopped, the reading was steady at 20 kV/m. The decay was exponential to 18-1/2 kV/m at 2130 and to 14 kV/m at 2206. The wigs were turned on and within 2 minutes, the signal was 5 kV/m. The wigs were then shut off and at 2210, the signal was zero at which time the sensor was shut off.

Tube. After Gunclean No. 1 was turned on (at 1445), this sensor began to indicate a charge and within 10 minutes, recorded 6 kV/m. The level gradually decreased to zero during the next 15 minutes and remained at zero for approximately another 15 minutes. Another period of increasing charge was recorded which looked much like the first. Still a third charge cycle was begun as before at about 1620, but at the end of this cycle (1945), a period of "high" charging (7-1/2 kV/m) occurred which reached a peak within 5 minutes and lasted until 1710. At 1710, the curve gradually returned to zero and by 1720, the level dipped below zero with one peak of less than a half minute at approximately 5 kV/m. By 1730, the reading was again positive. Guncleans Nos. 2 and 3 were turned on at this point. (All four were then on.) The curve reached a value of 7-1/2 kV/m at 1750 but immediately dropped to almost zero. During the next 20 minutes, the field level reached its maximum of about 8 kV/m. By 1815, the reading was again back to zero. During the next 12 minutes, the reading fluctuated around the baseline. At 1824, the reading again gradually increased to a peak value of almost 10 kV/m within 12 minutes. This value held until 1855. At that time, the reading decreased to 5 kV/m but within 10 minutes was again back to 10 kV/m.

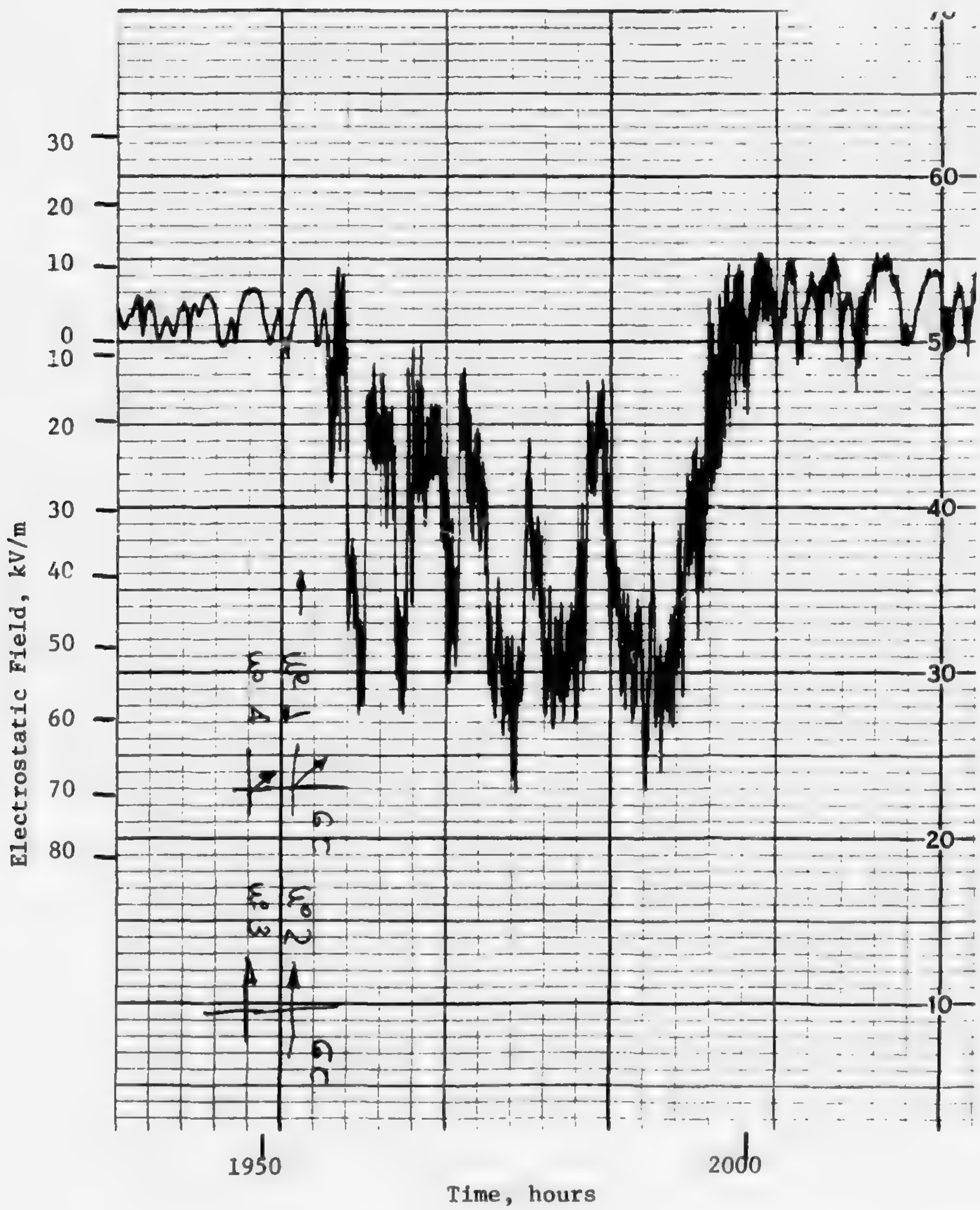


FIGURE 2. TYPICAL TRACE OF SIGNAL FROM WALL SENSOR SHOWING NEGATIVE SIGNALS SUPERIMPOSED ON POSITIVE

Within the next 5 minutes, the reading was again zero but immediately began a gradual climb to 14 kV/m by 1945, 20 kV/m at 2030, 21 kV/m at 2047, and 23 kV/m at 2120 when the guns were turned off. The value was still increasing slowly. Within 10 minutes, the final peak of 26 kV/m was recorded. That value held until 2145 when it began a slow decay. When the wigs were turned on at 2206, the decay was exponential to 10 kV/m with perhaps an indication of the start of an increase when the sensor was turned off at 2210.

Chevron. This sensor could not be used until the gunclean operation was completed. At 2135, the reading at 6 meters fluctuated between 115 and 130 kV/m. A profile at 1 meter, decreasing intervals from 9 meters, gave readings of 130, 125, 135, 115, 115, 95, 70, 42, and 20 kV/m. The value at 6 meters held until the wigs were turned on and it then decreased to a value of 15 to 25 kV/m within 3 minutes. No further readings were taken.

4.1.2 Tests in Tank 8P

For these tests, the tube sensor which was used in the center tank was physically transferred to the port tank. The Destator and the wall sensor were not the same units as used in the center tank.

4.1.2.1 Cleaning With Restricted Gun Rotation: Wigs Off. At the start of this test, the 3 guncleans were aimed at the bottom of the tank but were slowly rotated. Gun No. 1 was turned on at 1432, Gun No. 2 at 1435, and Gun No. 3 at 1437. Between 1452 and 1522, Gun No. 3 was off due to air motor failure. The guns were turned off starting with No. 3 at 1617, No. 2 at 1632, and No. 1 one minute later. Natural decay was watched until 1820. At that time, the wigs were turned on and operated in that mode for about 15 minutes, then all tests stopped.

Destator. Sensor D indicated no initial charge in the tank. At 1438, the sensor reading began an erratic rise and within 8 minutes was saturated above 15 kV/m. After the guns were turned off, an almost imperceptible decay began. The reading was still above 15 kV/m at 1800.

The decay was more rapid after that time with two sharp momentary drops at 1808 and 1816; but at 1820, the reading was still above 10-1/2 kV/m. The wigs then were turned on and the reading immediately dropped to zero and remained at that value with continuous fluctuations of as much as 1-1/2 kV/m into the negative.

Wall. Sensor W indicated zero field until after the guns were in operation except for a number of negative spikes. The spikes were all no larger than 10 kV/m except for one at 1417 which reached a value of 45 kV/m. After the guns were in operation, the readings were very erratic indicating first positive then negative fields with gradually decreasing amplitude until shortly after 1500. The readings were then steady at 1-1/2 kV/m. At 1522 (when Gun No. 3 was turned on), another period of wide fluctuations began in the readings. The values were again first negative and then positive and varied from 35 kV/m (negative) to as much as 50 kV/m (positive). This activity continued until Gun No. 3 was turned off at 1617. Within 5 minutes, the reading was steady at 3-1/2 kV/m.

After Gun No. 1 and No. 2 were turned off (1633), a very slow decay began. After a half-hour, the reading was still 1-1/2 kV/m. When the wigs were turned on, the value was about 1 kV/m and within 10 minutes, zero. The reading remained zero thereafter.

Tube. Three minutes after the guns were turned on, the readings began a slow exponential rise to a peak of almost 20 kV/m at 1615. This value started a very slow decrease after Gun No. 3 was turned off, and the rate of decay increased in an exponential fashion after Guns No. 2 and No. 3 were shut down. By 1645, the field value was 13-1/2 kV/m; at 1715, 8-1/2 kV/m; at 1745, 6 kV/m; and when the wigs were turned on, 5 kV/m. Immediately, the value fell to perhaps 1 kV/m; but within a minute, started to rise again. Within 5 minutes, during which there were several plateaus, a value of 7 kV/m was recorded. Following a period of slow decay to less than 5 kV/m, during the next 7 minutes, the field value rose in steps to 11 kV/m in the next 5 minutes (1835). At that point, the test was stopped.

Chevron. Sensor C, after a momentary drop to 4 kV/m after the guns were turned on, rapidly rose to a value of 32 kV/m within 8 minutes (1445), 80 kV/m at 1522, and 100 kV/m at 1545. The value continued to climb but more slowly until the guns were stopped. A maximum value of 115 kV/m was recorded at 1630. After the guns were turned off, the decay was exponential to 80 kV/m at 1640, 85 kV/m at 1645, 65 kV/m at 1700, and a low of 37 kV/m at 1817. The wigs were turned on at 1820 and the reading dropped immediately to 10 kV/m, then to 5 kV/m, and slowly increased to 20 kV/m by 1821. The meter reading then decreased but varied between 1 and 18 kV/m for the next several minutes. At 1825, the reading began to rise and indicated about 20 kV/m at 1835. When the wigs were turned off, the reading rose to 40 kV/m at 1840, but then decayed to 3 kV/m within 15 minutes, rose to 11-1/2 kV/m at 1934, and was 14 kV/m at 1952.

4.1.2.2 Cleaning With Normal Gun Rotation: Wigs On. (2 Guns) During these tests, the sensors were operating with the wigs on and with Guns No. 1 and No. 3 making the full washing cycle. Because of trouble with the air compressor, tests did not begin until 1000. At 1007, wigs were turned on. Gun No. 1 was on at 1044 and Gun No. 3 was on at 1149. Gun No. 2 was not used because of its proximity to the Destator. Wigs were turned off at 1300. Gun No. 3 was turned off at 1452 and No. 1 was off at 1453. Wigs were turned on at 1530 then off at 1534.

Destator. With the wigs on, the reading was zero and remained so until after Gun No. 1 was turned on at 1044. After about 10 minutes, a small reading was obtained -- under 1 kV/m. The magnitude gradually increased until the gun was stopped from about 1110 and to about 1115. During this period, the reading was again very low. About 1125, Gun No. 1 was again working and the reading increased to a peak of 1 kV/m. The reading varied considerably. After Gun No. 3 was turned on, the average magnitude, as well as the spikes, increased considerably. Some spikes were as large as 8 kV/m. In general, the readings were positive but some spikes were negative. Except for the spikes, none of the readings were greater than 2 kV/m.

When the wigs were turned off at 1300, the sensor immediately saturated. At 1328, the reading decreased exponentially to 6.5 kV/m within 4 minutes and remained at that level until 1337. This temporary decrease in reading, as well as succeeding drops at 1400 and at 1415, were attributed to hits by the gunclean water jet. At 1452, Gun No. 3 was stopped and at 1453, Gun No. 1 was stopped. At 1500, the reading began to fall. A minute later, the reading fell rapidly to 6 kV/m momentarily and then rose stepwise to 8.5 kV/m before decreasing to 3 kV/m at 1505. After an immediate rise to 7 kV/m, the reading fell to zero within 2 minutes and became very erratic. Recording was stopped at 1651. The sensor probably was not operating properly after the break in readings at 1500.

The Destator was removed for return to Cierva Electrooptical Corporation, Madrid, Spain.

Wall. After the Gun No. 1 was turned on, the sensor reading began to increase very slowly. At 1104, there was a sharp dip to 25 kV/m (negative) followed by an immediate rise to 20 kV/m (positive). Within 2 minutes, a maximum of 40 kV/m was reached with oscillations of as much as 10 kV/m. Within another 8 minutes (1114), the reading centered around zero with oscillations between 4 kV/m (positive) and 8 kV/m (negative). At 1120, the reading became steady at less than 1 kV/m but increased slowly to 1-1/2 kV/m at 1148. In the next 5 minutes, a gradual decrease to zero was recorded. A period of oscillations began at 1154 with excursions of first one polarity and then the other before reading a peak of 30 kV/m and subsequently decaying to zero. The variations were greater than 10 kV/m. After a 2-minute period of positive reading at 1215, a sharp drop to 30 kV/m (negative) was recorded with an exponential rise to a peak of 6 kV/m (positive). The frequency of oscillations reduced and between 1225 and 1235, the reading slowly decreased from 3-1/2 kV/m to 1-1/2 kV/m. During the next 15 minutes, the readings were again very erratic -- indicating principally positive charge but varying between positive and negative charges producing fields of 35 kV/m. These were probably periods during which the sensors were being hit by the spray.

After the wigs were turned off and until the guns were stopped (if the periods of erratic behavior are ignored), the reading gradually increased during the next 2 hours to a peak of 4 kV/m. After the guns were turned off at 1452 and 1453, the reading continued to climb to 5-1/2 kV/m and the curve was smooth. At about 1510, a 6-minute period of erratic readings was again recorded. (During this same period, the Destator and Chevron sensors were also giving erratic readings. The tube sensor was steady.) The reading again became steady and slowly decayed until the test was stopped at 1651. The final value was 2-1/2 kV/m.

Tube. The reading remained steady at zero until 1058. During the next 15 minutes, the peak reading climbed to 15 kV/m but dropped to 9 kV/m for a period of 6 minutes before starting a slow decay to 5 kV/m. After a low of 3-1/2 kV/m at 1135, the reading increased slightly then fell to 1-1/2 kV/m at 1150. For the next 15 minutes the reading rose steadily to a value of 16 kV/m. The reading then decreased to a value of zero at 1220 with some oscillations into the negative and again began a slow wavering rise to a maximum of 14 kV/m at 1255. At 1300, when the wigs were off, the reading temporarily decreased to 6 kV/m and then rose to a value of 18 kV/m by 1315. The reading was steady at this point for a period of some 10 minutes but then again was punctuated with the negative spikes. At 1345, a value of 21 kV/m was recorded. At 1445, a reading of 24 kV/m was indicated.

After the guncleans were stopped, the reading was 26 kV/m and a slow decay began. At 1529, the wigs were turned on and the reading went to zero, dipped to 6 kV/m (negative), returned to zero for a minute, and within 3 minutes was again 4 kV/m (negative). During the next 10 minutes, the curve exponentially returned to zero and remained at the value through the end of the test.

Chevron. This sensor was not used for any significant readings until 1454 after the guns were turned off. At that time, the reading was 150 kV/m; at 1500, 140 kV/m; at 1505, 132 kV/m; at 1512, 118 kV/m; and at 1515, 111 kV/m.

At this point, the sensor readings became erratic and the sensor would not zero.

4.1.3 Discussion of the Test Results in Gas-Free Tanks

The three sensors used by CincoTech were calibrated deliberately to have different sensitivities. The Destator sensors were most sensitive; both saturated at 15 kV/m. These were most sensitive because they provided the control point for the wigs. Therefore, one would expect that subtle changes in the field conditions in the tank would be more noticeable and first apparent at the Destator sensor. Sensor W, in the port tank, read 80 kV/m at full-scale deflection; Sensor T, used in both tanks, read 70 kV/m at full scale; and Sensor W, in the center tank, read 100 kV/m at full scale. Sensor C gave much higher reading but it was not the same size as the other sensors.

In studying the readings of the sensor readings, several items are apparent:

(1) In all the tests in the center tank, some residual field was measured with Sensor D when the sensor was turned on at the beginning of a new test. At the start of the several tests, the reading ranged from 2-1/2 to 7 kV/m. But, at the conclusion of some of the previous tests, the wigs had been turned on and a field of zero had been recorded. This contradiction may indicate that the Destator sensor is blinded by the wigs and that the actual field in the tank was never zero. Or, that the field is zero in the tank at the time the spraying is stopped but that due to mist settling or particle agglomeration or both, that a net field is gradually reestablished. (The residual field always indicated positive charge.) There is no record of field in the port tank at the beginning of a test but this is not particularly significant. The first day's tests were begun after the tank had been idle

since drydock and the second day the record does not show whether or not a field measurement was taken before the wigs were turned on.

(2) Because of the location of the wall sensors, they were repeatedly hit by the direct force of the water jet during the full washing cycle. Obviously, the sensors are rugged and -- based on these very short tests -- appear suitable for their intended environment.

(3) The Destator in the port tank malfunctioned during the second day of testing. It was pulled from the housing and packed for return to the factory.

(4) During all tests, the operation of the wigs reduced the maximum field as measured by the several sensors. The indicated increase in field between tests with the wigs on and the wigs off in the center tank, as indicated by Sensor W, was from 5 to 20 kV/m. The reading of the Destator sensor increased from about 1 to 15 kV/m (saturation); Sensor T from about 15 to 23 kV/m; Sensor C from about 40 to 115 kV/m. Thus, in all cases, the operation of the wigs did reduce the field.

(5) The field meter readings with Sensor C were several times larger than the readings with the CincoTech sensors. This is not surprising, and is, in fact to be expected as shown in Appendix A - Effect of Meter Size on Field Measurement.

4.2 Tests in Nongas-Free Tanks

Tests in the nongas-free tanks were conducted December 23 and December 24, 1975, while the S.S. Universe Japan was enroute from Bilboa, Spain, to Las Palmas, Canary Islands.

During these tests, the Chevron meter did not indicate any field within the tanks.

4.2.1 Tests in Tank 8C

These tests were performed with the wigs on and tank-washing procedures the same as would be used normally.

When the three sensors were turned on, all initially registered some field within the tank. The Destator sensor registered 15 kV/m (saturated); Sensor 3, located in a tube on the port side of the tank, registered 5 kV/m; and Sensor 1, located in a tube on the starboard side of the tank, registered 3 kV/m. All readings were "negative". After a period of 7 minutes, the Destator wigs were started and all field readings immediately dropped to zero and remained so until the guncleans were started.

At the start of the conventional washing cycle (four guncleans rotating in the usual programmed cycles), the readings of Sensors 1 and 3 rapidly rose to values of 17 and 18 kV/m, respectively, but the Destator sensor required 10 minutes to reach a value of only 2-1/2 kV/m. These high values recorded by Sensors 1 and 3 gradually decreased to 11 and 12-1/2 kV/m over the next half-hour. During the next 5 to 10 minutes, both sensors (1 and 3) indicated a positive field. After this short period, the negative readings were again recorded as shown on the graph. The reading on Sensor 1 continued to decay from 10 kV/m to zero. Sensor 3 indicated a field which varied between 16 to 22 kV/m for the next half-hour. Then, after a sharp positive pulse to 22 kV/m, returned negative to 10 kV/m and decreased to zero within a half-hour. Except for a few excursions to values of 4 to 5 kV/m, all readings remained at zero until the guncleans were turned off.

During these tests, hits on the sensors by the guncleans were definitely related to the spikes which were noted on both these traces.*

After all the guncleans had been off for some 15 minutes during which time all sensors recorded zero, the Destator wigs were turned off. The reading of the Destator sensor immediately began to rise indicating

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* Similar spikes also were recorded during the May-June tests.

a positive field. The slope of the trace appeared to be constant after 20 minutes. After another hour, the rate of increase appeared to be decreasing slightly. Readings were discontinued at this point. If the slope had remained constant, the Destator sensor would have required approximately 7 hours to saturate at 15 kV/m. At the time the readings were discontinued, the Destator sensor indicated 4 kV/m; neither Sensors 1 or 2 indicated any field.

Ten hours later, on the morning of December 24, the Destator sensor indicated a field of approximately 2 kV/m. No field was indicated by Sensors 1 and 3.

4.2.2 Tests in Tank 8P

At the start of the test in No. 8 port tank, inerting gas was being blown into the port tank through the forward hatch. Tube Sensor 3, closest to that hatch, registered a field of 12 kV/m. This value increased to 13 kV/m and then slowly decayed over the next 10 minutes to 10-1/2 kV/m. The Destator I sensor initially indicated a field of 1-1/2 kV/m, increased to 3 kV/m over the next 10 minutes, then rose to 5-1/2 kV/m within a minute. Sensor 1, located between the Destator and the aft guncleans, indicated no field.

Because of the continued rise in the Destator sensor reading and low air pressure readings at the Destator, it was deduced that the wigs were not operating. Subsequent examinations revealed that the air line at the Destator was dirty and the filter screen was plugged. These were cleared and tests were resumed. Guncleans 1 and 3 were in operation; because of its proximity to the Destator, Gunclean 2 was not used.*

During this washing cycle, the reading of the Destator Sensor was generally high and negative. The magnitude was at times 15 kV/m but

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* This Destator failed under test in this position during the May-June period and was removed from the tank for inspection at that time. Upon examination at the Cierva plant, the failure was attributed to a leaking seal which allowed water from the gunclean to enter the sensor. The sensor was repaired and reinstalled on December 23. The present failure was due to the use of a dirty air line obtained on-board the ship. After this obstruction was cleared, the Destator worked without further trouble throughout the test.

a true value of field would be difficult to predict because of the very erratic trace. The reason for the rapidly fluctuating trace was definitely related to the action of the gunclean jets. Direct hits by the jets were correlated with large spikes in the trace and other discontinuities possibly were caused by charge water droplets on the sensor element.

The trace for Sensor 3, the forward-most sensor, also indicated a wide fluctuation but the period was much slower than that of the Destator sensor. The majority of the values were positive and were the highest yet recorded -- three instances of fields greater than 35 kV/m were indicated. After a period of some 45 minutes from the start of the gunclean operation, the trace became somewhat smoother, and with only a few exceptions, the readings were negative until the guncleans were turned off after 4 hours into the test. After some oscillation, the indicated field values dropped to zero.

The trace for Sensor 1 was much smoother than the other two traces. Within just over a half-hour after start of the guncleans, the sensor recorded a field in excess of 30 kV/m (negative). The field then gradually decreased to a value of 7-1/2 kV/m by the time the guncleans were turned off, the trace continued to decrease over the next half-hour to a value less than 1 kV/m but not zero. The Destator sensor and Sensor 3 both indicated zero field within 2 minutes.

After the guncleans has been off for 1/2 hour and all sensors were indicating a very low or zero field, the wigs were turned off and the buildup of the field monitored.

The Destator sensor and Sensor 3 immediately indicated a return to a negative field, but Sensor 1 continued a slow decay toward zero. Within 20 minutes the Destator sensor indicated a field of 5 kV/m and slowly rising. Sensor 3, after a delay of some 7 to 8 minutes, started to rise but leveled off after 12 minutes at a value of 5-1/2 kV/m. Tests were terminated after another 10 minutes inasmuch as the rate of rise was very slow.

4.2.3 Discussion of Test Results in Nongas-Free Tanks

The evaluation of the results of these tests completed in the nongas-free, inerted, tanks revealed several interesting facts. In general, all values of field were "negative" whereas during the tests with the gas-free tanks all values were "positive". The readings obtained in the May-June tests increased to some value and remained constant while the guncleans were in operation. The December tests with nongas-free, inerted, tanks produced high reading at the beginning which gradually decreased with time. (Those results possibly indicate that a field meter reading could be indicative of the cleanliness of the tank. Washing a clean tank results in a "positive" charge and washing a dirty tank results in a "negative" charge.) These same polarity changes have been observed by other experimenters.[10, 11, 12]

5.0 GENERAL CONCLUSIONS AND COMMENTS

Based on the results obtained and observations made during the two periods, several positive conclusions can be enumerated.

(1) Operation of the wigs reduced the maximum field as measured by the several sensors.

(2) With the exception of the failure of Destator I, located in the port tank during the gas-free tests, all equipment functioned as expected.

(3) The wall sensors, due to their location, were repeatedly hit by the direct force of the water jet during the washing cycle. Obviously, the sensors are rugged and -- based on these very short tests -- appear suitable for their intended environment.

(4) The Destator in the center tank, after 6 months' inactivity, between the first and second test periods began working immediately and appeared to function as intended.

In addition to these conclusions, a number of pertinent comments are in order.

(1) The indicated field was reduced while the wigs were in operation. However, the extent to which this degree of charge suppression is important is unknown. The reading below which the tank is in a "safe" electrostatic condition has not been determined. The washing procedure should not be modified from present operating procedures based on these test results. At present, no readings or other indications from the CincoTech sensors justify using a more vigorous washing cycle. This statement is not meant in any way to reflect on the Destator or its operation but only to emphasize that a safe electrostatic level has NOT been determined.

(2) If a sensor reading is to be used to indicate charge density, it must be calibrated based on known charge levels. The presence of any meter will distort the field so that the field is no longer as it was before the sensor was in place.

(3) Some of the spikes in the traces in both the May-June and the December tests are definitely linked to the effect of the passing gunclean water jets. Other spikes are strongly suspected as being caused by charged water droplets impinging on the sensitive elements of the sensors.

(4) The failure of the Destator in the port tank during the first tests was attributed to a leaking seal which allowed water from the gunclean to enter the sensor. In a practical situation, means must be provided for shipboard repair and maintenance if these devices are to be used generally.

(5) The trouble with the same Destator at the beginning of the nongas-free tests was due to dirt in the air line. This failure is understandable but the situation can

happen. Therefore, the needs exist for a rapid indicator of wig failure and the development of an easy means of correction.

(6) At the end of several tests when the recorders were run after the guns and wigs were off, readings began to rise. This indicates the field is being reestablished possibly due to the settling of large droplets which, predominately, carry charge of one polarity. Several cycles of wig operation may be necessary to maintain a zero field in the tank. Perhaps the sensors should remain in operation to monitor the field for extended periods after the washing has ended. Some means to aid in the circulation of the mixture within the tank after the washing is stopped may aid in keeping a neutral charge in the tank.

(7) The Destator, by its inherent limitations, can only sense the average electrostatic field in the volume which it "sees" and will spray charged droplets to neutralize the effect of that field. As mixing of the mist occurs, pockets of charge will disappear and the average becomes the true level.

(8) The Destator can affect <u>only</u> those ignition sources associated with electrostatic charges and discharges. The Destator can have <u>no</u> effect on preventing explosions due to sparks, or other heat sources, originating from nonelectrostatic causes. The Destator and an inert gas system can <u>never</u> be used interchangeably.

6.0 REFERENCES

(1) January 26, 1970, Madoln Hareide, "Explosion on Board M/T Kong Haakon VII 29 December 1969". Preliminary Report Based on the Maritime Declaration and on Inspections Carried Out on Board by Representatives of the Norwegian Maritime Administration.

Electrostatic discharge is cited as one of five possible causes of explosion which produced extensive structural damage to the Kong Haakon during washing operation at sea.

(2) January 19, 1970, Report from Commander, Coast Guard Activities Europe, on Shell Oil Company Symposium held January 16, 1970, in London, England.

Similar and dissimilar aspects of three tanker explosions are reviewed. Investigation of several spark sources were reported under way including experiments on a sister ship. Static discharges associated with cleaning guns, falling objects, and metal cracks are listed.

(3) August 9, 1971, "Tanker Explosions". Memo to Office of Merchant Marine Safety from Merchant Marine Technical Division (D. E. McDaniel).

Nine large tanker incidents including four involving tank cleaning are listed. A review of 19 U.S. vessel incidents lists only one probably due to static charge. Tank size, tank cleaning systems, and coatings on tanks are suggested as factors that may have been significant in large tanker explosions. Inerting is suggested as preferred method of preventing explosions.

(4) November 30, 1971, "Interim Report Tanker Accident Study Committee", American Petroleum Institute, Division of Transportation, 1801 K Street, N.W., Washington, D. C. 20006.

Status report covering tank washing and gas-freeing operations, tank-washing procedures and atmosphere control, and possible iginition sources. Seven tanker explosions are listed. Conclusions and recommendations for continued studies are outlined including ship and shore studies of washing operations involving ungrounded objects, number of washing machines, charge density limits, and mist to ground discharges.

(5) October, 1971, William O. Wiley, Supervisor of Research, Richmond Research Laboratories, Texaco, Inc., "Tank Cleaning", Paper No. 5, International Tanker Safety Conference, Brighton, England.

Tank cleaning procedures to reduce explosion hazards are summarized. Findings to date in studies of electrostatics are reviewed to the effect that charged mists are generated by washing, charge decays to one-half value in about three hours in an unventiliated tank, and incendiary discharges are produced by passing isolated objects through charged clouds in laboratory tests. Need to minimize iginition hazard is seen even if tank atmosphere control procedures are used.

(6) March, 1972, W. M. Bustin, "Electrically Charged Mist Produced by Water Washing", Esso Engineering Report No. EESTMR 72, Esso Research and Engineering Company.

A series of tests were made in a 240-m^3 shore based rectangular tank with a Butterworth Type K washing machine in which the space charge was measured by collecting charged mist. The findings from 40 runs were that (1) hot water (180 F) produced twice the charge density as produced by cold water in a dirty tank, (2) small amounts of crude in the wash water had no great affect on charge density when the same crude was on the wall, (3) chemical additives in the wash water produced different effects, (4) charge decays at a rate proportional to the square of the charge density and limits the maximum charge density, (5) charge decay rate is not related to tank size, and (6) charge is uniformly distributed throughout the tank.

The rate of charge generation varied from 1 to 24 nanocoulombs/m^3 minute (0.4 to 9.6 x 10^{-8} amperes), and charge density generally in the range of 20 to 65 nanocoulomb/m^3 was reached in 10 to 40 minutes. Coagulation of the aerosol is proposed as a plausible explanation of the observed charge decay.

Shipboard tests on three tankers confirmed general level of charge and indicated a trend of lower charge density in larger tanks.

(7) de la Cierva, Juan, Umbert, M., and Leonard, G., "Destator Development Program Mid-Program Status Report", Cierva Electro-optical Corporation Report No. CEC-731, February 28, 1973.

(8) "Installation, Test, and Evaluation of the Destator - A Device to Enhance the Operational Safety of Bulk Petroleum Carriers", Marad Contract No. 4-37065, CincoTech Corporation Report No. D-74-2, February 6, 1974.

(9) "Installation, Test and Evaluation of the Destator - Test Program Formulation (Task I)", Revision 1, Marad Contract No. 4-37065, Cierva Electrooptical Corporation Report No. D-74-2, January, 1975.

(10) November 13, 1970, R. F. Lange, "Gas Concentration and Static Electrification Studies During Tank Washing on the S/S. Mobil Transporter", 70.34-AD, Mobil Research and Development Corp., Research Department, Paulsboro, New Jersey.

Gas concentration and static electrification were measured in 360,000 and 530,000-ft^3 tanks equipped with Butterworth washing machines. Twelve test runs were made in tanks of two sizes. Tests as reported were too limited and too many parameters were varied to justify many conclusions about the effect of tank size or wash water temperature on charge generation. Some conclusions appear valid: Dasic detergent produced a negative charge and decreased charge generation with 140 F wash water. With plain seawater, negative charges were generated from a dirty wall and positive charges from a clean wall. The number of washing machines used (2 to 6) did not greatly affect the charge level reached without detergent.

The "field" was uniform horizontally below the hatch cover. Corona probe measurements were variable and radio noise indicated electrical discharges occurred in the tank.

The conclusion that maximum "field" meter readup occurred at 25 to 30 feet below deck indicates that the potential was highest in the central area of the tank.

(11) March 26, 1971, R. F. Lange, "Gass Concentration and Static Electrification Studies During Tank Washing on the S/S. Mobil Meridan", 71.8-AD, Mobil Research and Development Corp., Research Department, Paulsboro, New Jersey.

Studies were made in 52,000 and 90,000-ft^3 tanks on a 50,000 DWT tanker during a 6-day voyage. Tanks were coated with Sovapon epoxy. Flammable mixtures were found in two of four tanks tested after cargo discharge. Gas concentration was not uniform and generally decreased during washing with Butterworth K machines. Findings included:

(1) Washing a dirty tank with clean seawater produced negative charges initially. When 125 F water was used, polarity reversed in 1.5 hours but polarity did not reverse after 3 hours when washing with 80 F water.

(2) Polarity reversal occurred quicker with 4 machines than with a single machine indicating faster cleaning. Maximum charge density was reached quicker with more machines (10 minutes - 4 machines, 180 minutes - 1 machine) but final charge level was the same.

(3) Detergents such as Dasic and Perolin at 550 ppm produced negative charges in clean and dirty tanks, but the level was lower in the dirty tank.

(4) Maximum "field" strength occurred 15 to 20 feet below deck level with either polarity charge and the "field" reading was reduced by grounded surfaces near the meter.

(5) Maximum positive or negative corona current occurred near the area of maximum "field" strength. Maximum radio noise occurred at slightly lower depths with positive charge but was nil with negative charge.

(12) March 6, 1973, B. Vos, "Influence of Contaminants and Electric Field Strength on Charge Generation", 2nd International Conference on Static Electricity, April 6, 1973.

This two-page paper relates the charge generated by impact of jets to the type and concentration of sea water contamination. Pure crude produces little charge. Mixtures of crude oil and sea water produce positive and negative sprays depending on concentrations. Surfactants can increase or decrease the charge. Charge densities reported range from 0 to 35×10^{-8} coulomb/m^3.

APPENDIX A

EFFECT OF METER SIZE ON FIELD MEASUREMENTS

In the tests on the Universe Japan, the field readings obtained with the Chevron meter were several times larger than the readings made with the Destator sensor in the same relative off-wall position at the same time. This result is not unexpected. Both are low impedance meters. The meters were calibrated in uniform fields produced by applying a potential on a flat plate in front of the vanes. This calibration is valid and the meters should read the same when placed in the plane of the wall of the tank containing a space charge. In this position, the flux density on the meters and at the wall is the same and the meters measure the true field at the wall regardless of the size of the meter. However, when the grounded meters are moved out into the tank, the meters distort the field in the tank. The meters then read the distorted field. The amount of distortion is a function of the meter size.

The effect of the meter size on the field measurement can be estimated by considering the field at the surface of a small grounded cylinder of radius, a, inside a larger grounded cylindrical tank of radius, D, containing a space charge. For the case where the cylinders are concentric, the field E, in the tank is

$$E = \frac{2\pi r\rho}{\varepsilon} - \frac{2\pi a^2\rho}{r\varepsilon} + \frac{4\pi a\rho}{r\varepsilon}\left(\frac{a}{2} - \frac{(D^2 - a^2)}{4a\ \ell n(D/a)}\right. \tag{1}$$

where r is the distance from the center of the tank, ρ is the charge density in the tank, and ε is the permittivity of the gas. This field is similar to the distorted field produced by inserting a grounded meter into the center of the tank. At the surface of the small cylinder, $r = a$, and the field measured by the meter is approximately

$$E_a = \frac{4\pi\rho}{\varepsilon}\left(\frac{a}{2} - \frac{D^2 - a^2)}{4a\ \ell n(D/a)}\right) . \tag{2}$$

When the tank is much larger than the meter, D >> a, this equation reduces to

$$E_a = - \frac{\pi \rho D^2}{\varepsilon a \ \ell n(D/a)} \tag{3}$$

If D = 200a, ln D/a will decrease from 5.3 to 4.6 if a doubles and will increase E by a factor of 1.15. However, when a doubles, $\frac{1}{a}$ decreases E by a factor of 1/2. Thus, doubling the size of the meter decreases the field at the side of the meter by a factor of about 0.57. Of course, this derivation applies to the field at the surface of the cylinder and at the center of the tank only. The situation is more complex at the end of a cylindrical surface such as a field meter and is different in positions other than at the center of the tank. Nevertheless, this simplified situation shows that the reading inside the tank is a function of the size of the meter. The readings for different meters can be accurate for the altered field but different in the same position in the same tank because the meters alter the field differently. Calculation of the original field strength, potential, or charge density in the tank from these readings is not recommended. Interpretation of the readings is complex and possibly even impossible in most cases. Calibration against a meter properly mounted on the wall of the tank is the only reliable method of calibrating a meter in another off-wall position in the tank and this must be done for every meter put in an off-wall position. Off-wall meter readings indicate presence of charge but should not be used to estimate safe levels of any sort unless they have been properly calibrated in the tank.

Some basis exists for determining the potential at the center of the tank by multiplying the field meter reading by a constant which is a function of the radius, a, of the field meter. The field intensity, E_a, at the surface of a low impedance spherical field meter inserted into a grounded spherical tank of radius, D, with space charge density of ρ is:

$$E_a = \frac{4\pi\rho}{3\varepsilon} \left(a - \frac{D}{2a} (D + a)\right) \tag{4}$$

When the radius of the tank is much larger than the radius of the meter (D>>a):

$$E_a = - \frac{2\pi\rho D^2}{3a\varepsilon} \quad . \tag{5}$$

Since the potential, V_o, at the center of the tank is $2/3\ \pi\rho D^2$, the ratio of the field at the meter to the original potential in the center of the tank prior to inserting the meter is:

$$\frac{E_a}{V_o} = - \frac{(2\pi\rho D^2)/3a}{(2\pi\rho D^2)/3\varepsilon} = - \frac{1}{a} \quad . \tag{6}$$

Thus, in the case of a spherical tank which is much larger than the spherical probe, a reasonable approximation of the potential that existed in the tank prior to introduction of the meter could be obtained by multiplying the field measured by the radius of the meter.

Practical tanks are not spherical; however, some work has been done in cylindrical tanks. In a similar grounded cylindrical tank of radius, D, and a low impedance cylindrical probe of radius, a, the field intensity, at the cylindrical surface of the probe is given by Equation 2.

The original potential, V_o, in the center of the cylinder before the grounded probe was inserted, is:

$$V_o = \frac{\pi\rho D^2}{\varepsilon} \quad , \tag{7}$$

and the ratio of the field meter reading to the original potential is:

$$\frac{E_a}{V_o} = \frac{2a}{D^2} - \frac{D^2 - a^2}{D^2 a \ \ell n(D/a)} \quad . \tag{8}$$

When the tank is much larger than the probe (d>>a), Equation 8 becomes:

$$\frac{E_a}{V_o} = \frac{1}{a^2 \ell n(D/a)} \quad , \tag{9}$$

and the field measured is no longer related to the original voltage in the simple manner as in the spherical tank (Equation 6).

In practice, a blunt-end cylindrical probe is lowered part way through a rectangular tank. Obviously, the relationship of the field at the

end of the probe where the sensor is located to the original potential will again be different and very complex. Although the ratio will be a function of the probe and tank size, the simple relationship described for the spherical tank does not apply.